

Practice of Epidemiology

Isotemporal Substitution Paradigm for Physical Activity Epidemiology and Weight Change

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Initially submitted December 22, 2008; accepted for publication May 18, 2009.

For a fixed amount of time engaged in physical activity, activity choice may affect body weight differently depending partly on other activities' displacement. Typical models used to evaluate effects of physical activity on body weight do not directly address these substitutions. An isotemporal substitution paradigm was developed as a new analytic model to study the time-substitution effects of one activity for another. In 1991–1997, the authors longitudinally examined the associations of discretionary physical activities, with varying activity displacements, with 6-year weight loss maintenance among 4,558 healthy, premenopausal US women who had previously lost >5% of their weight. Results of isotemporal substitution models indicated widely heterogeneous relations with each physical activity type ($P < 0.001$) depending on the displaced activities. Notably, whereas 30 minutes/day of brisk walking substituted for 30 minutes/day of jogging/running was associated with weight increase (1.57 kg, 95% confidence interval: 0.33, 2.82), brisk walking was associated with lower weight when substituted for slow walking (–1.14 kg, 95% confidence interval: –1.75, –0.53) and with even lower weight when substituted for TV watching. Similar heterogeneous relations with weight change were found for each activity type (TV watching, slow walking, brisk walking, jogging/running) when displaced by other activities across these various models. The isotemporal substitution paradigm may offer new insights for future public health recommendations.

body weight changes; epidemiologic methods; models, statistical; motor activity

Similar to total energy intake, total hours in a day are fixed and finite for an individual, and participating in one activity results in not participating in another. Parallel to the question of whether saturated fat is good or bad regarding the risk of coronary heart diseases (good if replaced for *trans*-fat but bad if replaced for polyunsaturated fat), the benefits of different physical activities depend not only on the specific activity but also on the activity it displaces. Different physical activities are very heterogeneous in their types, intensities, and, potentially, effects on body weight; the relative effects of each are not well described. For example, are different walking paces interchangeable? That is, would 30 minutes/day of brisk walking yield the same health benefits if it displaced an equal amount of time of slow walking, TV watching, sleeping, or another discretionary activity? Because displaced activities can be very heterogeneous and can generate different health effects, and because available hours for discretionary activities are limited, determining the relative effects of time spent in differ-

ent activities becomes of great importance to public health recommendations.

Whereas several observational studies have suggested that physical activity promotes long-term weight loss maintenance (1–5), other observational studies have failed to show any benefit (6, 7). Reasons for discrepancies in results include lack of statistical methods to elucidate the effects of different physical activity times and intensities on optimal health when displaced by other alternative activities. Willett and Stampfer (8) and Willett et al. (9) have discussed different modeling methods in nutritional epidemiology—the energy partition, standard multivariate (substitution), and others—to adjust for total energy intake when analyzing the associations between nutrient intake and health outcomes. Some of these concepts can be relevant in physical activity epidemiology.

To evaluate the effects of different physical activity forms, we compared the different methods described by Willett and Stampfer (8–10) using previously reported data

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on physical activity patterns and weight loss maintenance from the Nurses' Health Study II. We assumed a fixed available time while also considering the form of activity that is displaced.

MATERIALS AND METHODS

Study population

The Nurses' Health Study II is an ongoing prospective study of 116,671 US female nurses aged 25–42 years when they responded to a mailed questionnaire in 1989 about their medical history, lifestyle, and health-related behaviors. Follow-up questionnaires have been mailed biennially. Body weight was assessed on every questionnaire, physical activity was assessed on the 1991 and 1997 questionnaires, and a food frequency questionnaire has been included every 4 years starting in 1991. Additional details have been reported elsewhere (11). In this analysis, we included premenopausal women who originally had a 1989 body mass index of ≥ 20 kg/m², who had intentionally lost $>5\%$ of their weight between 1989 and 1991, and whose weight loss did not exceed 91 kg. Women were excluded if, at any point during follow-up, they had unreasonable data such as weight <38 kg or >182 kg, body mass index <15 kg/m² or >55 kg/m², or weight loss >91 kg; were no longer premenopausal in 1997; missed reporting their physical activity or weight in 1991 or 1997; reported activity values >240 minutes/day; were pregnant or within 12 months postpartum of reporting weight; or reported chronic conditions impairing exercise such as myocardial infarction, stroke, diabetes, or cancer anytime through 1997. After these exclusions, 4,558 women were eligible for this analysis.

Assessment of physical activity and sedentary behavior

In 1991 and 1997, participants were asked to report the average time spent per week during the previous year in each of the following 8 activities: walking or hiking, jogging (>10 minutes/mile (1 mile = 1.61 km)), running (≤ 10 minutes/mile), bicycling, calisthenics/aerobics/aerobic dance/rowing machine, tennis/squash/racquetball, lap swimming, or lawn mowing. For each activity, women chose one of the 11 duration categories that ranged from zero to ≥ 11 hours/week. Women also reported their usual walking pace in miles per hour: easy (<2), average (2–2.9), brisk (3–3.9), very brisk (≥ 4), or unable to walk. Moreover, women were asked to report the average number of flights of stairs they climbed daily. Stair climbing (minutes/day) was then estimated. Total discretionary activity (minutes/day) was considered the sum of the duration reported for each of the 9 activities. The questionnaire has been validated in a random representative sample of Nurses' Health Study II participants ($n = 147$) (11). Using past-week activity recalls and 7-day activity diaries as the referent methods, the correlation between activity reported on questionnaires and that of recalls was 0.79, and that reported on diaries was 0.62.

Hours/week of TV watching was used as a measure of sedentary behavior (i.e., inactivity) and was assessed in

1991 and 1997. Because TV watching has been associated with obesity (12) and thus confounds the associations with physical activity, it was included in our models. TV watching and the different physical activity types were all grouped under the umbrella of "total activity."

Other predictors and confounders

Weight was assessed at baseline (1991) and on each follow-up questionnaire through 1997. Baseline body mass index was calculated from height (1989) and weight (1991). Self-reported weight and height were strongly correlated in adults ($r = 0.97$) with measured weight and height (13). Because some diet components have been observed to be predictive of weight gain (14–17), they were included in the analysis. Using a validated food frequency questionnaire, we assessed intakes of sugar-sweetened beverages, energy-adjusted *trans*-fats, dietary fiber, and alcohol in 1991 and 1995. Values in both 1991 and 1995 were included in the model to account for changes in these covariates. Smoking status (never, past, current) at baseline and in 1997 was included in the models. Oral contraceptive use (never, past, current), parity (nulliparous; 1, 2, ≥ 3 births), and antidepressant use (never, past, current) in 1997 were included in the analysis. All these risk factors in addition to baseline age were controlled for in our statistical models.

Statistical methods

Pearson correlations were used to assess the associations among total activity components and with other covariates. Weight change from 1991 to 1997 was modeled as the outcome while adjusting for baseline weight. Successful weight loss maintainers were defined as those who did not regain $>30\%$ of their lost weight after 6 years. Three different multiple linear regression models (substitution, partition, and single activity) were used to assess the associations between 6-year changes in activity components and 6-year weight change.

The isotemporal substitution model, by definition, estimates the effect of replacing one physical activity type with another physical activity type for the same amount of time (e.g., replacing slow walking with TV watching, by taking TV watching out of the model). Substitution model A is expressed as follows:

$$\begin{aligned} \text{Weight change} = & (b_1) \text{ slow walking} + (b_2) \text{ brisk walking} \\ & + (b_3) \text{ jogging/running} \\ & + (b_4) \text{ other activities} + (b_5) \text{ total activity} \\ & + (b_6) \text{ covariates,} \end{aligned}$$

where b_1 – b_6 are coefficients of respective activities or covariates. By eliminating one activity component from the model (e.g., TV watching), the coefficient (b_5) for total activity represents the omitted activity component (TV watching). The remaining coefficients represent the consequence of substituting 30 minutes of that activity instead of TV watching while holding other activity types constant.

Table 1. Age-standardized Baseline Participant Characteristics, by Daily Levels of Discretionary Physical Activity, of 4,558 US Premenopausal Women Who Lost More Than 5% of Their Body Weight

	Physical Activity (1991), Minutes/Day				
	<10	10–20	21–30	31–60	>60
No. of women	954	799	720	1,191	894
Age, years (mean)	35.2	35.1	35.0	35.1	34.9
Total discretionary physical activity, minutes/day (mean)	5.1	14.3	24.5	42.5	96.0
TV watching, minutes/day (mean)	82.3	74.6	72.9	74.6	71.2
Slow walking, minutes/day (mean)	2.1	4.7	7.5	10.4	23.3
Brisk walking, minutes/day (mean)	0.7	1.9	3.8	7.8	18.9
Jogging/running, minutes/day (mean)	0.1	0.3	0.7	1.7	4.6
Other activities, ^a minutes/day (mean)	2.3	7.5	12.5	22.6	48.7
Body mass index in 1991, kg/m ² (mean)	24.2	24.0	23.8	23.6	23.5
Lost weight between 1989 and 1991, kg (mean)	–7.2	–7.3	–7.6	–7.8	–7.8
Energy intake, kcal/day (mean)	1,736	1,742	1,749	1,716	1,777
Alcohol intake, g/day (mean)	2.6	2.8	2.8	3.1	2.9
Sugar-sweetened beverage intake, ^b servings/day (mean)	0.5	0.4	0.4	0.3	0.3
<i>Trans</i> -fat, ^c g/day (mean)	3.4	3.3	3.1	3.1	2.9
Fiber, ^c g/day (mean)	17.4	18.0	18.8	19.3	21.0
Current smoking (%)	14.0	14.2	12.5	11.9	12.0
Oral contraceptive use (%)	12.9	12.9	14.4	12.5	13.1
Parity (mean)	1.7	1.6	1.7	1.6	1.5
Antidepressant use (%)	1.3	1.5	2.5	1.3	2.1

^a Other activities include biking, swimming, lawn mowing, aerobics, tennis, and stair climbing.

^b Sugar-sweetened beverages include sugar-sweetened carbonated beverages, punch, fruit drinks, lemonade, and ice tea.

^c Adjusted for total energy intake.

Similar interpretation for the remaining substitution models can be applied when other activity components are omitted from the model (refer to the Appendix).

The partition model partitions “total activity” among its components. As described by Willett (10), partition model F is expressed as follows:

$$\begin{aligned} \text{Weight change} = & (b_0)\text{TV watching} + (b_1)\text{slow walking} \\ & + (b_2)\text{brisk walking} \\ & + (b_3)\text{jogging/running} \\ & + (b_4)\text{other activities} \\ & + (b_6)\text{covariates.} \end{aligned}$$

In this model, the coefficient for one type of activity represents the effect of increasing this type of activity while holding other activity types constant. Therefore, it represents the effect of “adding” rather than substituting an activity type. Notably, total time for physical activity is not held constant, so this model is not isotemporal.

The single activity model, also not an isotemporal model, assesses each activity component separately (e.g., slow walking), without taking into account the other activity types, and is expressed as follows:

$$\text{Weight change} = (b_1)\text{slow walking} + (b_6)\text{covariates.}$$

Baseline weight was included among the covariates in all of our models. All tests used were 2-sided.

RESULTS

The 1991 baseline characteristics of the study population, by levels of discretionary activity, are outlined in Table 1. Active women had a lower body mass index at baseline; consumed more calories, alcohol, and fiber; and consumed less *trans*-fat and fewer sugar-sweetened beverages. They had fewer pregnancies and spent fewer hours watching TV. Baseline median discretionary activity was 27 minutes/day; 10% of the women reported zero or less than 5 minutes/day of total discretionary activity. Walking (slow plus brisk) was the most popular activity in this cohort, contributing to 45% of the total reported minutes/day.

The average weight loss between 1989 and 1991 was –7.6 (standard deviation, 4.9) kg, and the median was –5.9 kg. Only 20.5% of the women in the study population were able to maintain their weight losses for at least 6 years. These women exercised more than their counterparts and spent more time on brisk walking (10.8% of “total activity” time), jogging/running (2.9%), and other activities (20.3%)

Table 2. Percentage of Total Minutes/Day Contributed by Individual Activities in 1997, Stratified by Success of Weight Loss Maintenance, Among 4,558 US Premenopausal Women^a

	All Women (n = 4,558)	Maintainers of Weight Loss by 1997 (n = 934)	Nonmaintainers of Weight Loss by 1997 (n = 3,624)
Slow walking	7.9	7.5	8
Brisk walking	8.5	10.8	8
Jogging/running	1.7	2.9	1.4
Other activities ^b	16.7	20.3	15.6
TV watching	65.2	58.5	67

^a Successful long-term weight loss maintainers were those who lost >5% of their baseline weight in 1989 and did not regain >30% of the lost weight between 1991 and 1997.

^b Other activities include biking, swimming, lawn mowing, aerobics, tennis, and stair climbing.

and less time on slow walking (7.5%) and TV watching (58.5%) when compared with women who regained >30% of the lost weight (Table 2). The baseline correlations among the different activity components were weak (Table 3); however, the strong correlation ($r = 0.89$) between TV watching and “total activity” suggests a potential for confounding, especially because TV watching is associated with the outcome. As for the correlations between physical activity variables and other covariates in the models, the maximal correlation was 0.11.

Three different statistical models—substitution, partition, and single activity—were used to predict the associations between 30-minute increases in specific physical activity forms and weight regain (Table 4). The substitution models suggest that substituting a 30-minute/day increase in brisk walking for a 30-minute/day increase in jogging/running is associated with greater weight regain (1.57 kg, 95% confidence interval: 0.33, 2.82) (model 4D); however, substituting a 30-minute/day increase in brisk walking for a 30-minute/day increase in slow walking is associated with less weight regain (−1.14 kg, 95% confidence interval: −1.75, −0.53) (model 4B). Substituting a 30-minute/day increase in any physical activity type for a 30-minute/day increase in TV watching was associated with less weight regain (model 4A). The coefficient for “total activity” in these substitution models represents the activity component

dropped out of the model, that is, TV watching in model 4A, slow walking in model 4B, and so on.

Notably, the coefficients in the substitution model are identical to those in the partition model (model 4F), where “total activity” was partitioned. In this partition model, the estimated weight change associated with a 30-minute/day increase was significantly stronger for increased jogging/running (−3.26 kg, 95% confidence interval: −4.41, −2.10) than for brisk walking (−1.69 kg, 95% confidence interval: −2.15, −1.22), other activities (−1.26 kg, 95% confidence interval: −1.65, −0.87), slow walking (−0.54 kg, 95% confidence interval: −1.07, −0.02), or TV watching (0.47 kg, 95% confidence interval: 0.36, 0.59). Hence, for the same amount of increased activity time, the different activity intensities were associated with different degrees of weight regain (P for heterogeneity of coefficients <0.001). Moreover, calculating the difference in coefficients for the activities being compared in the partition model (e.g., brisk walking − slow walking = $-1.69 - (-0.54) = -1.15$) is equivalent to substituting one activity (brisk walking) for another (slow walking).

When each activity subtype was entered in the model one at a time, the results were not very different from those for the partition model. The exception was for slow walking, where the association with weight change became nonsignificant (−0.11 kg, 95% confidence interval: −0.62, 0.41) (model 4H).

DISCUSSION

Although the substitution and the partition models are mathematically equivalent, these models are interpreted differently because they elucidate different perspectives on the consequences of various forms of activity on weight change. The substitution model directly addresses a practical question that can be framed as an “isotemporal” analysis of engaging in one activity type instead of another. Whereas the same activity type can have heterogeneous effects in the substitution model, only one effect is estimated for each activity type in the partition model. Estimates from the partition model reflect the full effect of a certain activity subtype unconfounded by other activity types; however, it is not an “isotemporal” comparison, it does not account for the other activity’s time displacement, and it does not restrict

Table 3. Pearson Correlation Coefficients for Total Activity Components (Minutes/Day) for US Premenopausal Women at Baseline, 1991

	Total Activity ^a	TV Watching	Slow Walking	Brisk Walking	Jogging/Running	Other Activities ^b
Total activity	1.00	0.89	0.23	0.18	0.09	0.33
TV watching		1.00	0.02	−0.03	−0.04	−0.03
Slow walking			1.00	−0.23	0.01	0.10
Brisk walking				1.00	0.06	0.11
Jogging/running					1.00	0.08
Other activities						1.00

^a Total activity includes total discretionary physical activity and TV watching.

^b Other activities include biking, swimming, lawn mowing, aerobics, tennis, and stair climbing.

Table 4. Isotemporal Substitution of Activities, per 30-Minute/Day Increase and 6-Year Weight Change (Kilograms), for US Premenopausal Women From 1991 to 1997

Analysis Method	TV Watching		Slow Walking		Brisk Walking		Jogging/Running		Other Activities		Total Activity ^a	
	β_0^b	95% CI	β_1^b	95% CI	β_2^b	95% CI	β_3^b	95% CI	β_4^b	95% CI	β_5^b	95% CI
Substitution of activity to replace TV watching												
Substitution model A		Dropped	−1.02	−1.55, −0.48	−2.16	−2.64, −1.68	−3.73	−4.89, −2.57	−1.73	−2.13, −1.33	0.47	0.36, 0.59
Substitution of activity to replace slow walking												
Substitution model B	1.02	0.48, 1.55		Dropped	−1.14	−1.75, −0.53	−2.71	−3.97, −1.45	−0.72	−1.39, −0.04	−0.54	−1.07, −0.02
Substitution of activity to replace brisk walking												
Substitution model C	2.16	1.68, 2.64	1.14	0.53, 1.75		Dropped	−1.57	−2.82, −0.33	0.43	−0.22, 1.07	−1.69	−2.15, −1.22
Substitution of activity to replace jogging/running												
Substitution model D	3.73	2.60, 4.89	2.71	1.45, 3.97	1.57	0.33, 2.82		Dropped	2.00	0.77, 3.22	−3.26	−4.41, −2.10
Substitution of activity to replace other activities												
Substitution model E	1.73	1.33, 2.13	0.72	0.04, 1.39	−0.43	−1.07, 0.22	−2.00	−3.2, −0.77		Dropped	−1.26	−1.65, −0.87
Comparison of results vs. those from other nonisotemporal substitution models												
Partition model ^c F	0.47	0.36, 0.59	−0.54	−1.07, −0.02	−1.69	−2.15, −1.22	−3.26	−4.41, −2.10	−1.26	−1.65, −0.87		N/A
Single activity models ^d	0.48	0.37, 0.60	−0.11	−0.62, 0.41	−1.66	−2.11, −1.21	−3.44	−4.62, −2.26	−1.49	−1.88, −1.10	0.16	0.05, 0.27
	(model G)		(model H)		(model I)		(model J)		(model K)		(model L)	

Abbreviations: CI, confidence interval; N/A, not applicable.

^a Total activity includes total discretionary physical activity and TV watching.^b All models were adjusted for baseline (1991) age (years), weight (kilograms), and height (meters); total average alcohol intake (1991, 1995) (0, >0–<2.5, 2.5–5, >5–10, >10 g/day); sugar-sweetened beverage intake (1991, 1995) (0, >0–0.5, >0.5–1, >1 serving/day); energy-adjusted *trans*-fat intake (1991, 1995) (\leq 2.5, >2.5–3, >3–4, >4 g/day); energy-adjusted fiber intake (1991–1995) (5–15, >15–20, >20–25, >25 g/day); oral contraceptive use (1997) (never, current, past); smoking (1989, 1997) (never, past: >0–7 pack-years, past: \geq 8 pack-years; current: >0–19 pack-years, current: \geq 20 pack-years); parity (1997) (never given birth, 1 birth, 2 births, \geq 3 births); and antidepressant use (1997) (never, current, past).^c Total activity is partitioned among TV watching, slow walking, brisk walking, jogging/running, and other activities (biking, swimming, lawn mowing, aerobics, tennis, and stair climbing). Each regression coefficient (and 95% CI) represents a comparison of weight regain (in kilograms) for every 30-minute/day increase in the predictor variable, not restricting total physical activity time nor controlling the displacement of other activity time.^d Each component of total activity is entered separately in a single model.

total activity time. Hence, any observed association can still be confounded by “total activity,” and the comparative use of displaced activity time is not clear.

Several studies have attempted to assess weight regain predictors (2, 7, 18–20) or to establish physical activity guidelines necessary for weight loss maintenance (17); however, none of these studies accounted for other exercise types or their displacement. To our knowledge, although some studies used the partition model to account for other activity types (21, 22), none has used the isothermal substitution models to account for the displaced time. Other alternatives to assess the pure effect of a certain activity type were to confine the analyses to those persons who engaged in only the activity of interest (23, 24), which has many limitations. While doing so may control for confounding effects by other activity types, the caveats are the decrease in sample size and the potential overlap among the different activities types (e.g., people who run may start and end their training with walking). Therefore, all these issues make the isothermal substitution paradigm particularly valuable.

Isothermal substitution model (detailed considerations)

The number of hours in a day is finite and can be distributed among working, eating, sleeping, and discretionary time. However, not only can the activities in which one engages during discretionary time be highly heterogeneous between individuals (depending on socioeconomic status, occupation, and other social circumstances), but the relative expense and sacrifice of different activities displaced to partake in a period of activity may also vary widely. For example, although it may seem that a 1-hour walk by an unemployed individual should be equivalent to a 1-hour walk by a highly time-limited individual, the activity displaced by an unemployed individual (e.g., 1 hour of TV watching) is likely very different from the activity displaced by the busy individual (e.g., 1 hour of sleeping or jogging). Therefore, although the physiologic benefits of a 1-hour walk may be similar across individuals, the actual overall impact of a 1-hour walk may have a wide range of effects, depending on each individual's time limitations and general lifestyle. Hence, using isothermal analysis would eliminate such heterogeneity of partaken activities and/or displaced activities by carefully reframing the causal question as an isothermal substitution question of whether we walk instead of watch TV, or walk instead of jog/run, or exercise instead of sleep, for a given amount of time. In this investigation, the isothermal substitution model suggests that the different physical activity components are not interchangeable, nor are the different types of substituted activities. Whereas slow walking may appear protective against weight regain if it displaces an equal duration of TV watching, slow walking is not beneficial when displaced for brisk walking or jogging/running.

In a previous analysis (24), we showed that slow walking was protective for only those women who were overweight or obese. One possible reason is that women with excess weight engage in slow walking in displacement of watching TV, whereas lean women who engage in slow walking may

be displacing some moderate-to-vigorous activity time. For a lean person, walking slowly to the gym may be less efficient than driving to the gym if slow walking displaces their moderate-to-vigorous exercises. Conversely, for an overweight person, walking to the gym may be more efficient if it displaces their time watching TV. In this analysis, results were not stratified by baseline body mass index because it was beyond the scope of our study. The stratified analysis has been discussed elsewhere (24).

Another practical question can be framed in relation to total daily energy spent engaging in physical activities. For a given amount of calories spent per day, what is the most effective activity while investing time? By controlling for total calories spent on different activities, one can estimate the effect of isocaloric expenditure or substitution of energy spent on one activity for energy spent on another activity. Further analyses are warranted to address the various isocaloric-expenditure models.

The advantage of the isothermal model is it allows comparing substitution of a fixed time of an activity type for the same time engaged in another activity and thus helps answer the most relevant causal and public health question of how to spend our discretionary time for optimal weight control. This model also controls for the confounding effect of “total activity.” Just as total energy is a strong confounder in dietary analysis, total discretionary time is an important variable factor that has strong between-person variation and disease implications.

One disadvantage is that the results may be confusing; the coefficient for “total activity” reflects the activity component not included in the model and the remaining coefficients represent the effect of substituting an equal time of that activity for an equivalent time of the excluded activity. Another disadvantage is multicollinearity. Although some have suggested that a correlation coefficient of >0.6 should be carefully considered when included in a model (25), others view the removal of confounding as more important and think that collinear variables of up to 0.90 can still be reasonably controlled in various models, as was previously done (26, 27). According to the correlation matrix, there was little intercorrelation between the different forms of activity, although the correlation between TV watching and “total activity” was 0.89, which is expected given that TV watching constituted 65% of “total activity” time. Although some may argue that $r = 0.89$ is collinear, goodness-of-fit tests for models were adequate, and results were still able to distinguish important differences in weight change in different substitution models for TV watching. Ultimately, our data lacked information on sleeping duration and resistance training time. Had this information been available, we would have assessed the effect of one activity at the expense of sleeping duration on weight changes.

Other nonisothermal substitution models

Several alternative models exist for physical activity analyses that are important to discuss and compare with the isothermal substitution paradigm model, such as the partition and the single activity models. However, more

theoretical models, such as the residual and the density models, are beyond the scope of consideration for most analyses (refer to the Appendix).

Partition model. The methodological concepts of the partition model have been previously explained (10). Most fundamentally, the partition model does not adjust for total activity time but rather models all activities together in partitions of the activity type. Although the partition and substitution models are mathematically equivalent—the “substitution” coefficient can be derived and calculated from a contrast of estimates from a partition model (28)—the nature of the coefficient interpretations is not the same across the 2 methods. First, the regression coefficient in the partition model does not address what activity type is displaced by that physical activity coefficient (as a very specific reference group); thus, coefficients take on a heterogeneous comparison versus other activities. Second, because total activity time is not adjusted for and therefore not restricted in total time, coefficients in the partition model also reflect the effect of engaging in a greater volume (absolute quantity of time) of that particular physical activity type without regard to total available time—which is not a realistic model given that the amount of time in a day is always limited and finite. All in all, the partition model cannot answer the question about whether different physical activity components are time interchangeable regarding effects on weight.

Before choosing between the 2 models, one has to bear in mind that these models answer different questions. Physical activity is very heterogeneous when comparing slow walking, brisk walking, or other activities, where they have completely opposite effects. In the partition model, brisk walking exhibits only one effect; in the substitution model, it can have completely opposite effects. The same applies to slow walking and other activities. Thus, the effect of one activity type from partition modeling is wholly inadequate in characterizing the divergence of heterogeneous effects on body weight.

In terms of public health recommendations, physical activity guidelines have been provided by the US Department of Health and Human Services for people of all age groups (29). For adults, more than 20 minutes/day of moderate physical activity are needed for substantial health benefits, and more than 43 minutes/day are needed for more extensive health benefits. Almost half the duration was needed when adults engaged in vigorous physical activity. These guidelines were similar to our previous findings on physical activity needed for weight gain prevention (23) and weight loss maintenance (24). However, these results do not address the displaced time that is heterogeneous among people. In our current analysis, we provided refined estimates of defined activity time displacing other activities and defined effects on weight regain reduction. This alternative way of providing physical activity recommendations (stair climbing instead of slow walking, brisk walking instead of slow walking, etc.) may be useful in getting more people to meet the physical activity recommendations.

Single activity model. The single activity model shares many limitations with the partition model. Although the regression coefficients in this model were similar to those in the partition model because of the low correlations be-

tween activity types, this model has an added disadvantage and thus is not recommended for any physical activity–weight change analysis because it does not control for other activity types, total activity, or the activity being displaced. In essence, it has crude interpretability and limited applicability to physical activity epidemiology.

Ultimately, even though there will inevitably be some error in change in weight, random error in the dependent variable in linear regression does not bias estimates of regression coefficients. It is also established that correlated systematic within-person errors are often advantageously canceled when considering the difference in such variables within-person; hence, this problem should not be important.

Moreover, we acknowledge that our physical activity measurements were inevitably imperfect—which will tend to have underestimated the benefits of physical activity and overestimated the amount of physical activity needed to prevent weight gain—and there will always be measurement errors in physical activity assessments. However, this limitation has not prevented epidemiologists from identifying the importance of physical activity and disease in a variety of prospective cohort studies. Whereas objective measures of physical activity may have been desirable, they too are associated with error, and good validity of our physical activity questions has been documented (11). That said, because of the analogous nature of the isotemporal substitution paradigm to isocaloric substitution models in nutritional epidemiology, existing methods of correcting measurement error can be transferred from nutrition epidemiology (10) to physical activity epidemiology. Notably, advanced methods can be applied to account for many types of systematic, random, and between- and within-person measurement errors and variations (10, 30). In this particular example, where the exposure is physical activity change, measurement error correction would ideally require questionnaire validity assessment at 2 points in time separated by several years. Unfortunately, we are not aware of anyone with such data.

In summary, the isotemporal substitution paradigm elucidates a new way to model and investigate the effects of time engaged in different activities and varying displacement of other activities on weight change. The results of the isotemporal substitution paradigm will be more directly interpretable and meaningful to public health recommendations.

ACKNOWLEDGMENTS

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Dr. Mekary is supported by R25 grant CA098566 from the National Institutes of Health. Dr. Ding is supported in part by

a postdoctoral fellowship grant from the American Diabetes Association and by a grant from the Paul and Daisy Soros Fellowships for New Americans. The funding sources had no role in the study conduct and analysis and are not responsible for the views expressed in this paper.

The authors are grateful to Drs. I-Min Lee and Howard Sesso for their inspirational thoughts and discussions on these topics. They thank Susan Malspeis for SAS programming assistance and Lisa Li for SAS program review (SAS Institute, Inc., Cary, North Carolina).

Drs. Mekary and Ding, who contributed equally to the study and the manuscript, had full access to the study data and take responsibility for the integrity of the data and the accuracy of data analysis. Conception and design: Drs. Ding and Mekary; data acquisition: Drs. Mekary and Willett; data analysis and interpretation: Drs. Mekary and Ding; drafting of the manuscript: Drs. Mekary and Ding; critical revision for intellectual content: Drs. Mekary, Willett, Hu, and Ding; statistical expertise: Drs. Mekary and Ding; administrative, technical, or material support: Drs. Willett and Hu; study supervision: Dr. Ding.

Conflict of interest: none declared.

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APPENDIX

Substitution models

For interpretations, refer to the Discussion section of the text. Baseline weight is included among the covariates.

Model A: TV watching is taken out of model A.

$$\begin{aligned} \text{Weight change} = & (b_1) \text{ slow walking} + (b_2) \text{ brisk walking} \\ & + (b_3) \text{ jogging/running} \\ & + (b_4) \text{ other activities} \\ & + (b_5) \text{ total activity} \\ & + (b_6) \text{ covariates.} \end{aligned}$$

Model B: slow walking is taken out of model B.

$$\begin{aligned} \text{Weight change} = & (b_0) \text{ TV watching} + (b_2) \text{ brisk walking} \\ & + (b_3) \text{ jogging/running} \\ & + (b_4) \text{ other activities} \\ & + (b_5) \text{ total activity} \\ & + (b_6) \text{ covariates.} \end{aligned}$$

Model C: brisk walking is taken out of model C.

$$\begin{aligned} \text{Weight change} = & (b_0) \text{ TV watching} + (b_1) \text{ slow walking} \\ & + (b_3) \text{ jogging/running} \\ & + (b_4) \text{ other activities} \\ & + (b_5) \text{ total activity} + (b_6) \text{ covariates.} \end{aligned}$$

Model D: jogging/running is taken out of model D.

$$\begin{aligned} \text{Weight change} = & (b_0) \text{ TV watching} + (b_1) \text{ slow walking} \\ & + (b_2) \text{ brisk walking} \\ & + (b_4) \text{ other activities} \\ & + (b_5) \text{ total activity} \\ & + (b_6) \text{ covariates.} \end{aligned}$$

Model E: other activities are taken out of model E.

$$\begin{aligned} \text{Weight change} = & (b_0) \text{ TV watching} + (b_1) \text{ slow walking} \\ & + (b_2) \text{ brisk walking} \\ & + (b_3) \text{ jogging/running} \\ & + (b_5) \text{ total activity} \\ & + (b_6) \text{ covariates.} \end{aligned}$$

Partition model (model F)

For interpretations, refer to the Discussion section of the text. Baseline weight is included among the covariates.

$$\begin{aligned} \text{Weight change} = & (b_0) \text{ TV watching} \\ & + (b_1) \text{ slow walking} \\ & + (b_2) \text{ brisk walking} \\ & + (b_3) \text{ jogging/running} \\ & + (b_4) \text{ other activities} \\ & + (b_6) \text{ covariates.} \end{aligned}$$

Residual model (e.g., TV watching taken out of the model)

Baseline weight is included among the covariates.

$$\begin{aligned} \text{Weight change} = & (b_1) \text{ slow walking residual} \\ & + (b_2) \text{ brisk walking residual} \\ & + (b_3) \text{ jogging/running residual} \\ & + (b_4) \text{ other activities residual} \\ & + (b_5) \text{ total activity} + (b_6) \text{ covariates.} \end{aligned}$$

Residuals indicate whether a certain activity component is as “expected” at a given “total activity” amount. Nevertheless, unlike caloric intake, which is homeostatically regulated, the amount spent on discretionary activities is probably not that well regulated and is highly variable within a month or a year. Thus, the concept of a 5-minute excess or deficit of physical activity over homeostatically regulated total physical activity becomes inapplicable, unlike for total calories, which makes the residual model less relevant in physical activity epidemiology.

Density model

Baseline weight is included among the covariates.

$$\begin{aligned} \text{Weight change} = & (b_1) \text{ percentage of slow walking from} \\ & \text{total activity} \\ & + (b_2) \text{ percentage of brisk walking} \\ & \text{from total activity} \\ & + (b_3) \text{ percentage of jogging/running} \\ & \text{from total activity} \\ & + (b_4) \text{ percentage of other activities} \\ & \text{from total activity} \\ & + (b_5) \text{ total activity} + (b_6) \text{ covariates.} \end{aligned}$$

The estimates represent the effect of substituting a percentage of one activity component for a corresponding percentage of the omitted component, similar to the substitution method. However, unlike nutritional intake, physical activity is given in absolute amount (e.g., 30 minutes/day of moderate-to-vigorous physical activity) and not as a percentage. In addition, a certain percentage of “total activity” may be very heterogeneous among individuals. Hence, it would be difficult to interpret and translate into practical recommendations, which makes the density model inappropriate in physical activity epidemiology.